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Occupational Dose Estimates for the National Ignition Facility

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Abstract

The National Ignition Facility (NIF) is currently being constructed at Lawrence Livermore National Laboratory (LLNL). During peak operation, the NIF will attain D-T fusion yields of 20 MJ in a single experiment and 1200 MJ/y. With such high yields, neutron activation will be important within the NIF Target Bay. The total dose equivalent (dose) will be maintained ≤ 10 person-rem/y with individual doses ≤ 500 mrem/y, and all doses will be as low as reasonably achievable (ALARA). This work outlines planned maintenance activities, expected dose rates, and the resulting worker dose. Methods for the reduction of this dose are discussed, and a tool for the rapid calculation of the occupational dose is presented.

1. Introduction

During NIF D-T operations, as many as 4.3×10^{20} 14 MeV neutrons will be generated per year. As a result, prompt doses and neutron-induced activation must be considered. Neutron activation will be significant in structures, equipment, and experimental packages. The Department of Energy (DOE) has committed to maintaining the NIF total occupational dose to ≤ 10 person-rem/y.[1] The ALARA principle will be applied to all doses. It is only through a detailed analysis of the maintenance requirements (frequency, duration, and location) and calculation of the residual dose rates that one can estimate the occupational dose. Using such an analysis, facility "stay-out" times and the need for auxiliary shielding may be determined.

The present work details anticipated maintenance needs as well as expected residual dose rates. These are combined to estimate the annual occupational dose and identify methods of reducing this dose. Auxiliary shielding methods and possible facility modifications are discussed along with their possible effects upon the cumulative occupational dose. A tool for rapidly calculating the minimum occupational dose for an arbitrary shot sequence is presented. Plans for use of this tool in reducing the occupational dose are discussed.

2. Facility overview

The NIF Target Bay is a concrete cylinder with an inner radius of 15.24 m and walls 1.83-m-thick. 192 laser beams penetrate the Target Bay wall and propagate in 2 × 2 arrays. After reflecting off mirrors within the Target Bay, the beams meet at the center of a 10-m-diameter target chamber. The exterior of the chamber will be covered with 40 cm of "gunite" (sprayable concrete) shielding. *Figure 1* shows a cross section of the NIF Target Bay.

Attached to the target chamber are 48 final optics assemblies (FOAs). The FOAs include four integrated optics modules, which include frequency conversion crystals, diffractive optics, a focusing lens, and debris shields for each beam. Stainless steel panels are mounted to the inner surface of the target chamber to serve as beamdumps for stray laser light. The panels are louvered to capture a large percentage of material that gets ablated from the surface by x-rays emanating from the target. Additional penetrations in the target chamber enable diagnostics and vacuum pumps to be mounted, targets to be inserted, and allow for access to the chamber interior by personnel and equipment.

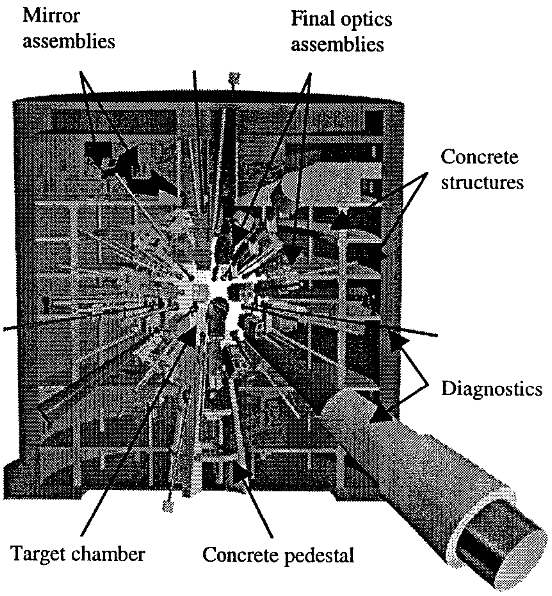

Fig. 1. A cross section of the NIF Target Bay reveals the target chamber, its concrete pedestal, diagnostics, and other various within the building.

All of these components are subject to neutron activation, and thus, need to be included in maintenance activities and estimates of occupational doses.

3. Methods and assumptions

Calculation of occupational doses requires the use of a computer code system and a set of assumptions regarding the operation of and maintenance throughout the facility. These items are now described.

3.1 Computer code system

A system of computer codes has been used to calculate the residual dose rates from NIF systems following yield operations. Calculations begin with the TART98 and TARTCHEK codes.[2] TART98 is a three-dimensional (3-D) Monte Carlo neutron and photon transport code. TART98 features 50-, 175-, and 566-group neutron structures that result in great speed compared to other Monte Carlo codes. TARTCHEK is an interactive geometry visualization and error-checking code and is essential in the development of complicated models. TART is used to calculate energy-dependent neutron fluxes. These fluxes are used as an input to subsequent neutron activation calculations.

The TARTREAD code is used to interactively interpret the TART output and automatically create input files for activation calculations.[3] TARTREAD prompts the user for selection of zones of interest, materials of choice, and an irradiation sequence. TARTREAD greatly speeds the creation of the many activation input files needed for detailed analyses.

Nuclide inventories have been calculated with the ACAB radionuclide generation and depletion code using the FENDL/A-2.0 activation cross section library.[4-5] A 1993 study sponsored by the International Atomic Energy Agency identified ACAB as one of only two codes that were "suitable and satisfactory" for detailed fusion calculations.[6] ACAB is able to fully account for the pulsed nature of the irradiation.

Following neutron activation calculations, TART98 is used again to transport decay photons from the most important radionuclides to locations where workers might be during maintenance activities. Photon fluxes are converted to dose rates using fluence-to-dose conversion factors adopted by the American National Standards Institute.[7]

The set of computer codes and the calculational procedure described above have been benchmarked against experiment using the Rotating Target Neutron Source (RTNS) for concrete activation studies.[8] Additional benchmarking with RTNS is planned to increase confidence in code predictions.

3.2 Radiation protection models

The radiation protection calculations have been divided into two parts. First, an integrated model was created for much of the Target Bay. This model includes the first wall, target chamber, gunite shielding, target chamber flanges and pedestal/cup, concrete structures and walls, plenum and plenum plug, utilities, cables and cable trays. The penetrations in the target chamber and concrete floors are accurately simulated. The model is used to provide dose rates in about 35 different locations throughout the Target Bay. *Figure 2* is a plot of the integrated model. In the second part, detailed models have been created for some of the key systems. These include the FOAs, transport cryostat and target positioner, diagnostic instrument manipulators, turning mirrors and structures, beamtubes, vacuum system, target chamber passive damping system, catwalks, and floor bracing beams. *Figure 3* shows a view of a portion of the FOA model and is a good example of the typical level of detail that is needed. When dose rates are needed for a particular task, dose rates at a given location in the integrated model are added to those for a specific system.

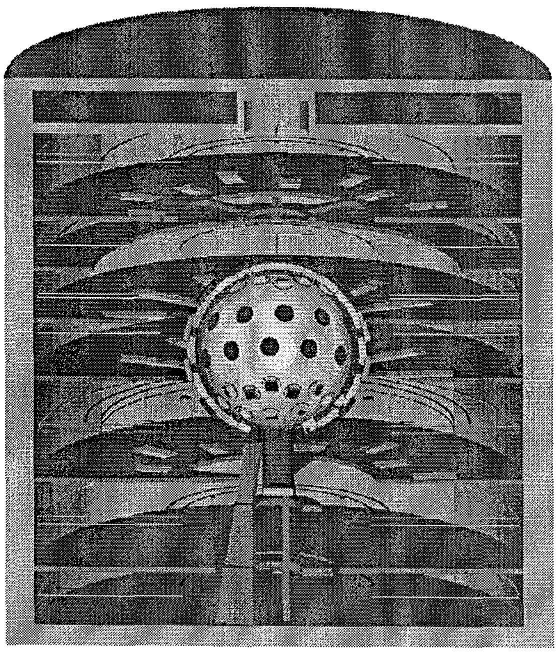

Fig. 2. Visible in this plot of the integrated model are the chamber, gunite shielding, port plugs, concrete structures and walls, and some utilities and cable trays.

3.3 Operational scenarios

In order to calculate activation levels and the resulting dose rates, operational scenarios had to be assumed. Here, two such scenarios are described and results are given for each.

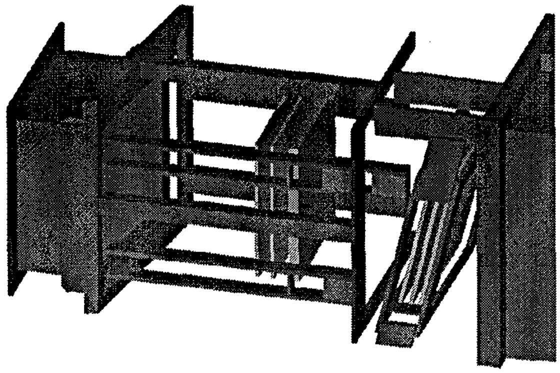

Fig. 3. This view of the FOA model shows the vacuum window assembly (left) and an integrated optics module with its outer walls removed (debris shield, diffractive optics, focus lens, and frequency conversion crystals are visible right to left).

The first operational scenario is intended to represent a situation that might occur early in the ignition campaign. This scenario assumes a large number of shots without high fusion yields. Due to the large number of shots, many tasks such as target insertion and diagnostic manipulation occur frequently. The second operational scenario is intended to represent a mature facility. In this scenario, the full facility yield of 1200 MJ/y is assumed. In this type of operation very few, if any, non-yield shots will be possible due to the required stay-out time of 5 days following each 20 MJ yield. For this analysis, it is assumed that the year will consist only of sixty, 20 MJ shots. *Table I* specifies the number and type of shots that are assumed for each scenario.

Table I. Two different operational scenarios have been analyzed for occupational doses.

	# of experiments/year	
Shot type	Scenario #1	Scenario #2
Non-yield	520	0
100 kJ	52	0
1 MJ	12	0
20 MJ	6	60
Annual shots	590	60
Annual yield	137.2 MJ	1200 MJ

In scenario #1, a facility turn-around time of 8 hours is assumed. That is, 8 hours is the minimum time needed to prepare the facility to perform the next experiment. In scenario #2, improvements and increases in operational efficiency are assumed which reduce this time to 4 hours. In order to allow long-lived radionuclides to build up, 10 years of operation is assumed in scenario #2. Scenario #1 assumes only 3 years of operation.

Immediately following high-yield experiments, excessive dose rates within the NIF Target Bay will prohibit entry. Depending upon the yield, the stay-out time can be a great as 5 days. The availability of NIF is estimated at 72%. It is assumed here that the facility will have an "effective availability" of 320 days per year. The extra days are available, because there will be significant overlap between periods of maintenance on the laser and the Target Bay stay-out time. Available days can be used for maintenance, stay-out time, or shot set-up and execution.

3.4 Maintenance activities

Activities vary greatly in their frequency, location, and duration. Obviously, one must insert and align a target for every experiment. Cleaning/change-out of the first wall, on the other hand, is expected to occur only twice per year. *Table II* shows the major maintenance activities and subtasks for some of these.

Table II. The frequency and duration have been estimated for major maintenance activities.

Task or sub-task	Location	Duration (person-hr)	Frequency
Final optics assembly maintenance:			
- Debris shield change-out	- chamber	48/cycle	52 cycles/y
- Diffractive optics change-out	- chamber	48/cycle	12 cycles/y
- Vacuum isolation valve service	- chamber	1/unit	12 units/y
- 3ω calorimeter service	- chamber	2/unit	96 units/y
- Integrated optics module change-out	- chamber	16/unit	160 units/y
- Debris shield refurbishment	- workstation	96/cycle	52 cycles/y
- Integrated optics module refurbishment	- workstation	30/unit	160 units/y
Target chamber maintenance:			
- Install/remove lift	- lift	2/cycle	8/cleaning
- Remove/replace plenum plug	- plenum	16/cycle	8/cleaning
- Transportation of first wall panels	- 5 m from cart	20/cleaning	2 cleanings/y
- Unloading/loading of first wall panels	- contact with panels	13/cleaning	2 cleanings/y
Target insertion and characterization:			
- Access to target housing	- target housing	6/target	Varies
- Remove crushable foam and nosecone	- workstation	0.5/target	with
- Cryostat inspection and refurbishment	- workstation	4/cryogenic target	scenario
- Install target/fill/layering/etc.	- target housing	12/cryogenic target	
Diagnostics manipulation/maintenance:			
- Diagnostic instrument manipulators	- manipulator	16/week	All sub-tasks
- Static x-ray imager	- diagnostic	2/week	occur
- Neutron spectrometer	- diagnostic	4/week	52 week/y
- Other on-chamber diagnostics	- chamber	16/week	
- Other off-chamber diagnostics	- Target Bay	8/week	
- Diagnostic set-up/check-out	- chamber/workstation	120/week	
Vacuum system maintenance	- pumps	16/cycle	2 cycles/y
Mirror maintenance:			
- Mirror change-out	- mirrors	4/unit	52 units/y
- Mirror refurbishment	- workstation	10/unit	52 units/y
Prompt doses:			
- NIF personnel (direct and skyshine)	- Control Room and Diagnostics Building	N/A	All yield shots
- LLNL personnel (skyshine)	- LLNL site		

Location is important and has been accounted for in the calculation of the dose rates for each task or sub-task. For example, although debris shield change-out occurs near the target chamber by necessity, debris shield refurbishment takes place at a cleaning workstation outside of the Target Bay. Therefore, workers performing refurbishment tasks only will receive a dose from the activation products within the debris shield and frame plus tritium and debris deposited on their surfaces.

Some of the values in *table II* have been experimentally confirmed. The change-out of debris shields, for example, has been practiced on prototype components, and it takes 1 person about 15 minutes to remove a debris shield and replace it with a new unit. For 192 debris, this would translate into 48 person-hours. For many of the tasks and sub-tasks, the duration is only an estimate. While it is believed that these are conservative estimates, they will be updated and improved upon during the early years of NIF operation.

4. *NIFDOSE* spreadsheet

To enable the rapid calculation of occupational doses for multiple operational scenarios, the *NIFDOSE* spreadsheet has been created. *NIFDOSE* allows the user to input the number of shots of each type and key parameters such as turn-around time. The user also is able to specify whether or not certain features are available. Examples include the target chamber service robot, an additional set of debris shields and frames, and shielding plugs within the FOAs.

For a given set of shot types, turn-around time, and assumptions, *NIFDOSE* determines the stay-out duration for shots of each type. The stay-out times are selected to minimize the total occupational dose subject to the scheduling constraints. Dose rates that a worker would experience while performing a given task are contained within *NIFDOSE* and must be updated in order for new tasks or methods to be incorporated.

Future versions of *NIFDOSE* will include additional tasks and sub-tasks and will include options for the user to identify multiple types of local auxiliary shielding.

5. Projected doses

Occupational dose estimates are now presented for the two baseline scenarios. Key tasks are identified, and suggestions for reduction of the dose are presented.

5.1 Baseline scenario #1

The intent of scenario #1 is to simulate the early years of NIF operation with cryogenic targets and significant fusion yields. The scenario assumes 10 non-yield shots per week along with weekly 100 kJ yields, monthly 1 MJ yields, and a 20 MJ yield every other month.

Even with a yield of only ~ 140 MJ/y, the target chamber service robot is absolutely essential. If the first wall and beam-dumps are cleaned manually, it would result in an occupational dose of about 6.0 person-rem per cleaning. Clearly, operating in this manner is not possible. All remaining doses assume that the robot is available.

With a total of 590 shots and a turn-around time of 8 hours per shot, about 197 days is needed just to set-up for each shot. Thus, only 123 days are available for use as stay-out time. Given the assumptions made for this scenario, the minimum dose occurs if 0.88 days of stay-out time are used following each 100 kJ yield, 3.38 days are used after 1 MJ shots, and 6.14 days are used after 20 MJ shots. The total occupational dose for this scenario is 6.77 person-rem. Note that no stay-out time has been designated for the non-yield shots. That is, the dose is minimized if only the 8 hour turn-around time follows each non-yield shot. If even an additional 4 hours is allocated for each of these shots, then about 87 days of stay-out time would no longer be available, and the dose would rise dramatically to ~ 38 person-rem. In reality, one would be forced to reduce the number of experiments in order to accommodate the delay and stay below the 10 person-rem limit.

For the optimized scenario #1, FOA maintenance dominates the total dose with a contribution of 4.71 person-rem. Debris shield change-out alone is responsible for 3.73 person-rem. After FOA maintenance, target insertion and characterization is the second most important task with work at the target access housing contributing 0.63 person-rem.

Due to the large portion of the dose (55%) that results from debris shield change-out, there is a large incentive to reduce the frequency, duration, and/or dose rate for this task. One potential solution has been identified. A simple shielding plug has been designed that would be inserted inside the weldneck flange. It would reduce the neutron fluence in the FOA structures, and thus, reduce their contribution to the dose rate. Although these shielding plugs will not be fielded during the initial installation of the FOAs, provisions have been made to install them at a later date. The design of the plugs has yet to be optimized, but a preliminary design would reduce the FOA maintenance dose in scenario #1 from 4.71 to 3.72 person-rem. Since the FOAs also make a significant contribution to the dose rate during several other tasks, the total dose would be reduced by an additional 0.17 person-rem to only 5.61 person-rem.

5.2 Baseline scenario #2

The second scenario assumes the facility is operated at its maximum annual yield of 1200 MJ. If the facility were to achieve this annual yield, it would not be possible to perform additional experiments unless individual shots could attain greater than 20 MJ of yield. While one can only speculate if the facility would ever be operated in the manner described by scenario #2, it is useful to estimate the occupational doses as a means to identify areas in which the greatest reduction might be achieved.

With only sixty shots and a 4 hour turnaround time, a full 310 of the 320 days are available for use as stay-out time in scenario #2. This results in a stay-out time of 5.17 days per shot. The total dose in this case would be 20.98 person-rem without the FOA shield plugs and 17.63 person-rem with them. Once again, FOA maintenance is the most important task and debris shield change-out it the most important sub-task. They contribute 14.23 and 9.56 person-rem, respectively, in the case with FOA shield plugs (17.33 and 11.69 person-rem without the shield plugs).

Due to use of the robot, target chamber maintenance only contributes 0.16 person-rem to the annual dose. Without the robot, this would jump to ~ 65 person-rem/y. When the robot is used, removal and installation of the plenum plug (the plus must be removed to allow the robot to enter the target chamber) is the most important sub-task at 0.13 person-rem. Obviously, a method for the automatic manipulation of the plenum plug is desirable.

Target insertion and characterization contributes 1.54 person-rem with work at the target access housing responsible for 0.81 person-rem. 6 person-hr per target is probably an overestimate, but this cannot be absolutely determined until the cryogenic target positioner is fully designed and tested.

Diagnostic maintenance and manipulation contributes 0.99 person-rem, but this is dominated by diagnostic set-up and check-out (0.67 person-rem). It is reasonable to expect that a mature facility producing 1200 MJ of fusion yield per year would not require development and testing of new diagnostics. Thus, this item probably overestimated.

Vacuum system and mirror maintenance activities make only minor contributions to the total dose (0.06 and 0.20 person-rem, respectively).

Prompt doses within and around the facility amount to 0.45 person-rem. This is roughly divided between direct doses to personnel in the Main Control Room and

Diagnostics Building and skyshine dose to personnel around the LLNL site.

5.3 Reduction of doses

When attempting to reduce the dose received by workers, one typically relies upon three basic concepts: time, distance, and shielding. In addition to these methods, one can switch traditional materials for low-activation replacements or provide for multiple sets of key equipment.

By reducing the time that a worker is exposed to a given dose rate, the total dose is also reduced. One example of this is the target chamber robot. Since the robot is to be used, NIF personnel will not have to enter the target chamber on a regular basis. This reduces their time of exposure essentially to zero.

The FOA shielding plugs are one form of shielding. When present, they reduce the neutron activation of the FOA components, and thus, reduce the dose rate to which a worker might be exposed. Alternatively, one could place γ-ray shielding between activated components and the workers. In the case of the FOAs, such shielding would be prohibitively large and would inhibit the workers' progress. It may be possible, however, to place auxiliary shielding in some areas. If shielding is placed near the target positioner, doses received by personnel inserting or removing target assemblies may be reduced. Temporary shielding walls may be used in this capacity.

Increasing the quantity of some components helps by reducing the dose rate at the time when maintenance activities are performed on the items. If, for example, multiple transport cryostats are available, then they can be refurbished on a rotating basis following 1-2 weeks of radioactive cooling time. If six units are available, the target insertion and characterization dose drops from 1.54 to 0.94 person-rem in scenario #2. If an additional set of debris shields are frames is available, the FOA maintenance dose falls by at least 0.33 person-rem. Similar reductions would be possible if additional integrated optics modules are available.

Since the FOA makes significant contributions to the dose rate in many areas of the Target Bay, previous work addressed the possibility of replacing portions of the FOA with low-activation carbon composites.[9] The main drawbacks to such a proposal are the increased cost (composites are estimated to be 3-5× as expensive as aluminum components) and the development that would be required. Composites also have potential issues related to their performance in a vacuum (e.g., outgassing) and exposure to scattered laser light and x-rays emanating from the target.

When constructed from an aluminum alloy, the vacuum isolation valves (VIV) will cost approximately $30K each. Thus, the incremental cost for carbon composite fabrication would be $2.9-5.8M for the 48 units that are needed. Since the VIVs will initially be constructed from aluminum, the replacement cost might be as high as $7.2M. This does not include the facility downtime that would be needed to implement such a modification. If the change were made, the dose reduction might be as high as 5-6 person-rem/y. Assuming 20 years of operation, this corresponds to 100-120 person-rem and a cost-benefit ratio of $60-72K per person-rem saved. This is several times the typical ALARA guidance of $2.5-25K.

Replacement of the 3ω calorimeter spool (another component of the FOA) is estimated to cost $2.2-3.6M. The dose reduction from this replacement would be ~ 3 person-rem/y. Again, the cost-benefit ratio is well above ALARA guidance, but such a replacement still may be needed to reach the dose limit of 10 person-rem/y.

The combination of replacement of the VIVs and 3ω calorimeter spools with carbon composites and optimized shielding plugs within the FOAs is estimated to reduce the total occupational dose in scenario #2 to about 14 person-rem.[9] This, in conjunction with an extra set of debris shields and frames and a fleet of six transport cryostats, would reduce the dose to ~ 13 person-rem. Additional improvements in efficiency and auxiliary shielding will be needed to reach the dose limit of 10 person-rem.

6. Conclusions/recommendations

The present work has provided estimates of the occupational doses that will be experienced during two scenarios for NIF operations. In scenario #1, moderate yields and a large number of shots were assumed. Results suggest that the annual occupational dose will be well below the 10 person-rem limit. In is clear, however, that the target chamber robot must be available. In the scenario #2, 1200 MJ/y operation has been assumed. Due to the required stay-out time of ~ 5 days per shot, one would have to forego any non- or low-yield experiments. The baseline occupational dose would be ~ 21 person-rem. Some simple modifications and additions could reduce this dose to ~ 16 person-rem. Replacement of VIVs and 3w calorimeter spools with carbon composites would reduce this further to ~ 13 person-rem.

The reader should be cautioned that many assumptions and placeholders have been necessary to complete this work. Diagnostics, the transport cryostat, and other components have not been fully designed, and thus, expected designs have been modeled. As the designs of these components progress, radiation protection considerations must be part of the process and the designs must be incorporated into worker dose analyses.

Material compositions, especially those of the target chamber, concrete structures, and the FOAs, must be measured an the actual compositions need to be incorporated into dose rate estimates. Such work is currently underway and needs to be continued.

Finally, these analyses need to be improved as more information related to the way in which the facility will be operated becomes available. Frequency and duration of maintenance activities are crucial to accurate occupational dose estimates. Close collaboration between operations personnel and radiation protection experts is needed.

Acknowledgments

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